Design of the TMT mid-infrared echelle: science drivers and design overview

J. H. Elias[a], J. S. Carr[b], M. J. Richter[c], J. Najita[a], M. R. Chun[d], A. T. Tokunaga[e], M. Liu[e], J. Lacy[f], S. Strom[a], M. Liang[a], T. W. Bond[e]
[a]National Optical Astronomy Observatory, 950 N. Cherry Ave, Tucson, AZ 85719
[b]Naval Research Lab, Remote Sensing Div., Washington, DC 20375
[c]University of California, 1 Shields Ave, Davis, CA 95616
[d]Institute for Astronomy, University of Hawaii, 640 North A'ohoku Place, #209, Hilo, HI 96720
[e]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Dr., Honolulu, HI 96822
[f]University of Texas, Austin, Department of Astronomy RLM 16.332 Austin, TX 78712

ABSTRACT

We present a discussion of the science drivers and design approach for a high-resolution, mid-infrared spectrograph for the Thirty-Meter Telescope. The instrument will be integrated with an adaptive optics system optimized for the mid-infrared; as a consequence it is not significantly larger or more complex than similar instruments designed for use on smaller telescopes. The high spatial and spectral resolution possible with such a design provides a unique scientific capability. The design provides spectral resolution of up to 120,000 for the 4.5-25 μm region in a cross-dispersed format that provides continuous spectral coverage of up to 2% to 14 μm. The basic concept is derived from the successful TEXES mid-infrared spectrograph. To facilitate operation, there are separate imaging channels for the near-infrared and the mid-infrared; both can be used for acquisition and the mid-infrared imaging mode can be used for science imaging and for guiding. Because the spectrograph is matched to the diffraction limit of a 30-m telescope, gains in sensitivity are roughly proportional to the square of the telescope diameter, opening up a volume within the Galaxy a thousand times greater than existing instruments.

Keywords: infrared instrumentation, spectrograph, Thirty-Meter Telescope

1. INTRODUCTION

The next generation of extremely large telescopes (aperture ~30 m) potentially offers enormous gains in sensitivity for diffraction-limited observations, in addition to gains in spatial resolution of roughly a factor of 3 over existing facilities. For background-limited observations carried out at the diffraction limit, the speed of observations increases as roughly D^4.

The increased sensitivity with such large apertures is sufficient, for high spectral resolution in the mid-infrared, to offset the lower background obtained in space, as is shown schematically in Figure 1. This figure shows approximate sensitivities at a wavelength of 10 μm for selected existing and planned facilities, both ground-based (TEXES and MICHELLE) and space-based (Spitzer and JWST/MIRI). The sensitivity plotted, noise-equivalent line flux (NELF) is the flux in an unresolved line in erg-cm^{-2}-sec^{-1} measured with 1 sigma in 1 second (equivalent to 10 sigma in 100 seconds). The point labeled "MIRES" is the expected performance for an instrument similar to TEXES[1] on TMT[2] (30-m aperture).

For background-limited observations, the NELF for a given facility is proportional to the inverse square root of spectral resolution, while for detector-limited observations it is independent of resolution. This means that a mid-IR spectrograph on the Thirsty-Meter Telescope (TMT) with a resolution $R=\lambda/\Delta\lambda \sim 1000$ would have significantly poorer sensitivity than JWST (though significantly better than Spitzer). Conversely, a high-resolution instrument on JWST (assuming its size and mass could be accommodated, which in fact it could not) would be detector-limited, and would therefore gain much less in sensitivity relative to a ground-based instrument on TMT. A telescope aperture of roughly 100 m is required to provide the same low-spectral-resolution sensitivity as JWST.

Ground-based and Airborne Instrumentation for Astronomy, edited by Ian S. McLean, Masanori Iye,
Proc. of SPIE Vol. 6269, 62693U, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.670439

Report Documentation Page

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **Design of the TMT mid-infrared echelle: science drivers and design overview**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Research Laboratory,Remote Sensing Division,Washington,DC,20375**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

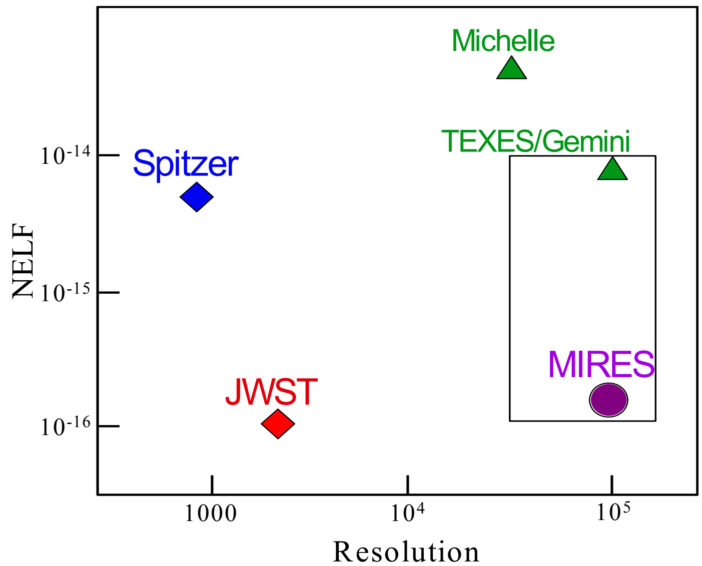

Figure 1. Comparison of 10-μm sensitivity vs. spectral resolution for selected ground- and space-based facilities. NELF is sensitivity to an unresolved emission line, as defined in the text.

In addition, of course, the spatial resolution of TMT will be roughly a factor of 5 greater than that of JWST and a factor of 3 greater than that of current ground-based facilities. Interferometers (e.g., VLTI[3]) do provide equivalent spatial resolution – or better – but currently have limited sensitivity and are inefficient in dealing with complex spatial structures.

A mid-infrared instrument on TMT would therefore exploit science in two areas: objects measured at high spectral resolution (roughly 100,000) or at high spatial resolution. In the sections that follow, the primary science case for these capabilities is outlined, followed by a discussion of the design requirement derived from the science case. A concept for the instrument and adaptive optics system that would fulfill these requirements is presented elsewhere in these proceedings[4,5,6].

In the course of developing the TMT facility concept, a detailed science case has been assembled[7], concentrating on a handful of critical scientific problems that cannot be addressed by other facilities, including those expected to be operating by the time of TMT first light (for the mid-infrared, specifically including JWST/MIRI). These questions range from probing the origins of the universe to understanding the ways in which stars and planets form. In the following section we discuss those aspects of the TMT detailed science case that can be addressed *uniquely* by a high spectral resolution mid-infrared instrument.

2. TMT MID-INFRARED SCIENCE CASE

The Mid-Infrared Echelle Spectrograph (MIRES) on TMT will provide a tremendous leap in sensitivity and speed for high-resolution spectroscopy and high-spatial resolution imaging in the thermal infrared (5-25 μm). As we describe below, these gains translate into the opportunity to explore new scientific frontiers as well as to address fundamental, long-standing problems in astrophysics. To provide specific examples of these opportunities, we focus here on the ability of MIRES to address some of the most compelling problems of our time: the origin of planetary systems and the origin of life on Earth.

The discovery of giant planets surrounding nearby stars has lent new scientific urgency to, as well as significant public interest in, understanding whether planetary systems like our own are rare or common occurrences. We already know that Jupiter-mass planets are relatively abundant around solar-type stars. The questions of the future are then centered

on understanding how systems with giant planets formed, whether these systems also formed terrestrial planets, and whether and how life might emerge in such systems.

By the time TMT sees first light (~2015), searches for terrestrial planets will have been carried out from space, with Kepler (~2008) measuring planetary transits and SIM (~2011) measuring stellar reflex motion. Searches for terrestrial planets will also have been made from the ground through precision radial velocity studies of substellar objects (e.g., Gemini/PRVS ~2010). Significant investments will also have been made toward detecting and characterizing the light from extrasolar planets. Sophisticated ground-based coronagraphs (e.g., Gemini/ExAOC) will study the light from giant planets surrounding nearby stars, and from space TPF may at some time in the future be detecting the light from terrestrial planets surrounding nearby stars.

Studies with MIRES on TMT will be critical to completing the picture of planetary system formation. While many other facilities will focus on characterizing the diversity of planetary systems, MIRES provides a uniquely powerful tool for probing planet formation environments for clues to the physical origin of this diversity. While ALMA will study the outer regions of planet-forming disks, only MIRES can provide a direct look at the inner disk regions (the 1-10 AU region) where terrestrial and giant planets form.

Spectroscopic studies with MIRES, targeting the gas in disks, the interstellar medium, comets, and other environments, also offer the opportunity to explore the plausibility of an extra-terrestrial origin for the prebiotic compounds that led to the emergence of life on Earth. MIRES imaging of debris disks will explore mechanisms by which water and prebiotic organic compounds may have been delivered to planetary surfaces. These studies will be highly synergistic with ALMA, which will probe the outer regions of planet-forming and debris disks, and JWST, which will mainly probe molecular constituents in the solid phase (i.e., ices).

MIRES will also contribute to the characterization of planetary systems. Spectroscopy with MIRES will probe the atmospheres of close-in extra-solar giant planets for clues to their formation histories. Imaging of debris disks with MIRES will probe outer solar system architectures, particularly those involving lower, Neptune-mass, planets. These approaches are highly complementary to other planet detection techniques.

2.1. Strengths and versatility of MIRES

The versatility of MIRES in addressing astrophysical issues arises from the richness of the mid-infrared region of the spectrum, which includes spectral features of atoms, ions and molecules. Hence, spectroscopy at these wavelengths can be used to probe gas in environments ranging from planetary atmospheres, to cool molecular clouds, HII regions, and active galactic nuclei. Mid-infrared molecular spectroscopy is particularly well suited to probing the physical conditions and chemistry in protostellar envelopes and the inner planet formation regions (< 5AU) of disks. The mid-infrared also allows us to observe environments over a range of extinction, even those that are obscured by fifty or more magnitudes of visual extinction.

Furthermore, emission from dust in a variety of astrophysical environments reaches a maximum at mid-infrared wavelengths. High-spatial, high-contrast imaging with MIRES will provide an exquisitely detailed look at the spatial structure of these regions.

The high-resolution spectroscopic capability of MIRES provides the kinematic information that is critical to solving a host of astrophysical problems. It also enables the detection of spectral features that cannot be measured at low-spectral resolution, because of either confusion due to spectral crowding or weakness of the very narrow lines characteristic of low temperature regions. For ground-based spectroscopy, $R \geq 30,000$ allows us to observe spectral features in narrow windows between strong telluric lines. In addition, spectral features that fall within telluric lines can often be measured by observing at times of the year when the radial velocity of the source shifts the feature away from the telluric line. High resolution also substantially reduces the thermal background, making ground-based instruments competitive with lower resolution space-based spectrographs.

Illustrations of the kinds of diagnostics that are available in the mid-infrared are shown in Figure 2, below. It is worth noting that much of the work done to date has focused on CO transitions at 4.7 μm, in large part because current facilities do not have the sensitivity to work at longer wavelengths, which are in fact rich in diagnostic information (see Figure 2b).

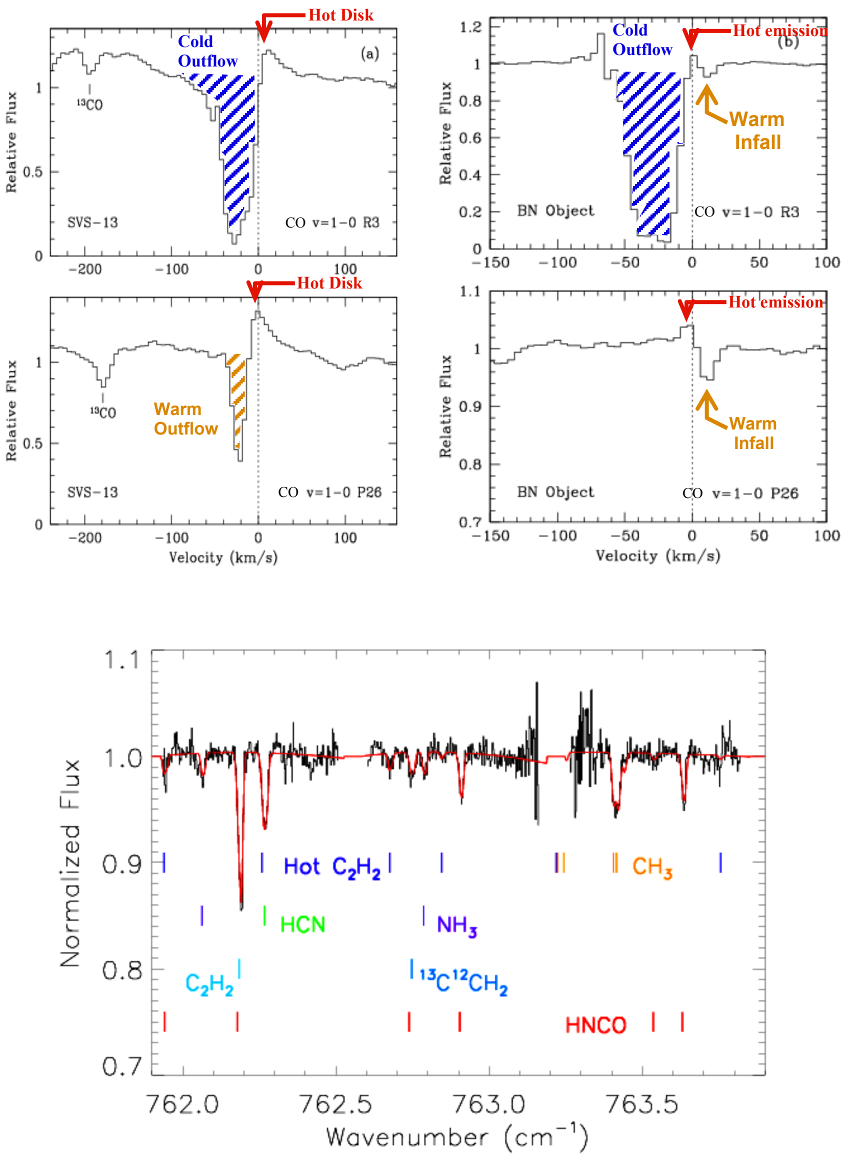

Figure 2. Examples of complex structure observed at high spectral resolution. One can compare spectra from two different 5-µm CO transitions in two different objects (top [8]) and also see an example of the range of diagnostics available at longer wavelengths [9].

For high-resolution mid-infrared spectroscopy, the gains due to a 30-m aperture with diffraction limited images are truly impressive, with 2–4 orders of magnitude increase in speed over current mid-infrared echelle spectrographs on existing large telescopes. The comparisons to cooled spaced based instruments are also impressive. Due to the combination of large telescope aperture and low background per resolution element at high dispersion, the sensitivity of MIRES to an unresolved spectral line is comparable to that of the planned MIRI spectrograph (R~2000) on the 6-m JWST (see Figure 1). Hence, ground–accessible mid-infrared spectral lines measured with JWST can be observed at higher resolution with MIRES to obtain valuable information on kinematics.

For mid-infrared imaging, no ground-based facility will come close to JWST for raw sensitivity. However, MIRES on TMT will have 5 times the spatial resolution of a 6-m JWST, and this will make MIRES the choice for imaging when angular resolution rather than sensitivity is the primary consideration. Moreover, the point source sensitivity of MIRES is sufficient to enable high-spatial resolution imaging of many sources detected by the Spitzer Space Telescope. While the gains in spatial resolution are 3-4 times over that of existing telescopes, the increases in the strehl ratios due to the AO systems planned for the TMT era are equally important by enabling high-contrast imaging. In particular, the diffraction-limited capability of MIRES (<0.1 arcsec at 10 μm) enables detailed imaging of complex dust structure (at ~1 AU resolution) around nearby stars.

2.2. The nature of mid-infrared discovery space

The high sensitivity of MIRES translates into a significant discovery space. Since only a few astronomical sources of any kind have been accessible thus far at high-spectral resolution due to sensitivity limitations (i.e., only the tip of the luminosity function), MIRES offers the opportunity to study fainter and more diverse populations and potentially discover new phenomena. The ability to study large samples of a class of objects, rather than just the brightest ones, means that MIRES can have a large impact on particular problems, such as understanding the formation of planetary systems as discussed below.

The high sensitivity of MIRES also gives us the ability to measure very weak spectral features in high signal-to-noise spectra, for example, to aid in the detection of rare molecular species. This potentially significant discovery space has implications for our understanding of the origin of life on Earth through the measurement of organic molecules that are precursors to complex prebiotic compounds. The high sensitivity also allows the exploration of a wider range of wavelengths, including those with poorer telluric transmission where important spectral features are known to be present (e.g., 24μm [FeI] line).

2.3. MIRES key science: origin of planets, life and stars

Since their discovery ten years ago, extra-solar planets have revealed an ever-increasing variety in their orbital properties, i.e., in mass, orbital radius, and eccentricity. This diversity, both remarkable and largely unanticipated, sparks a number of questions. What are the physical mechanisms that govern the formation of such systems? Do they commonly produce solar systems like our own? How does life arise on these systems? Answering these questions represents a significant challenge to theory. Thus far, many physical processes that are plausibly significant for planet formation and the origin of life have been identified, but understanding which of these dominate and how they fit together into a global picture of planet formation requires the guidance of observations.

In the sections below, we discuss specific examples that illustrate the variety of approaches that can be taken with MIRES to address these issues.

2.3.1. Probing planet formation environments

Expansion of our limited knowledge of the properties the inner regions of planet-forming disks (< 10 AU) represents a significant science opportunity for MIRES. In comparison, the outer reaches of circumstellar disks, beyond 50-100 AU, have been well studied over the last two decades with continuum and spectral line observations at millimeter wavelengths. In the future, both the SMA and ALMA will extend similar observations inward to smaller radii. However, these facilities will typically be unable to probe disks at yet smaller radii, within a few AU.

Probing this region of the disk is critical for our understanding of planet formation. All the terrestrial and giant planets in our Solar System and all the known extra-solar planets have orbital radii in this range. Planets are likely to form and to radially migrate through this region of the disk. Much of what we currently know about disks at these radii (e.g., their properties and lifetimes) derives from dust emission in the near- to far-infrared, both continuum measurements and low-resolution spectroscopy of solid-state features.

Much more detailed information can be obtained by studying the *gaseous* component of disks, which comprises the bulk of the disk mass during the early epoch of planet formation. The physical and chemical structure, the dynamics, and the lifetime of the gas are all important properties in establishing the architectures of planetary systems. In the last several years, progress has been made in developing the observational techniques and theoretical framework that are

needed for such studies. High-resolution *near-infrared* spectroscopy has been successful in probing the very inner regions of disks (< 1AU). The major impact of MIRES will be to extend these studies to a larger range of disk radii, to a statistically significant number of systems, and to rarer molecular species. These advances derive from the sensitivity and mid-infrared wavelength coverage of MIRES. As a result, such studies are well beyond the capability of current generation telescopes, even ones that may be equipped with instruments comparable to MIRES in the decade prior to the commissioning of MIRES on TMT.

MIRES will provide an unparalleled capability to study gas in the inner planet-formation regions (< 10 AU) of protoplanetary disks. Firstly, it targets a spectral region that is ideally suited to probing the region of the disk within 10 AU. At the warm temperatures (100 - 5000 K) and high densities of disks at these radii, molecules will be both abundant and sufficiently excited to produce rotational and ro-vibrational spectra in the infrared. Atomic transitions are also available as diagnostics of the hot innermost disk and of heated irradiated disk surfaces. Secondly, with the spectral resolution of MIRES, we will be able to obtain velocity-resolved line profiles. Although inner disks are typically too small to resolve *spatially* at the distance of the nearest star forming regions, we can utilize the Keplerian rotation of disks to separate disk radii *in velocity*, and derive the radial variation of the line intensity by fitting resolved line profiles. By observing and modeling multiple ro-vibrational transitions from multiple molecular species, the radial variation of column density, temperature and molecular abundances can be determined.

These general spectroscopic techniques can be used to probe the physical and chemical structure as well as the dynamics of disks. Studies of the *evolution of the gas content* of disks will probe the dominant pathways for giant planet formation and the origin of the masses and eccentricities of terrestrial planets, issues that are closely related to habitability and the likelihood of solar systems like our own. Studies of the *dynamical and chemical structure* of disks will probe the nature of turbulence and mixing in disks. These studies will bear on the long-standing issue of the mechanism responsible for disk accretion, the growth of grains and planetesimals, and the survival of terrestrial planets against rapid inward migration. Studies of the *physical structure* of disks may enable the indirect detection of giant planets in the process of formation. Such measurements would address the extent to which planets migrate inward from the radii at which they form.

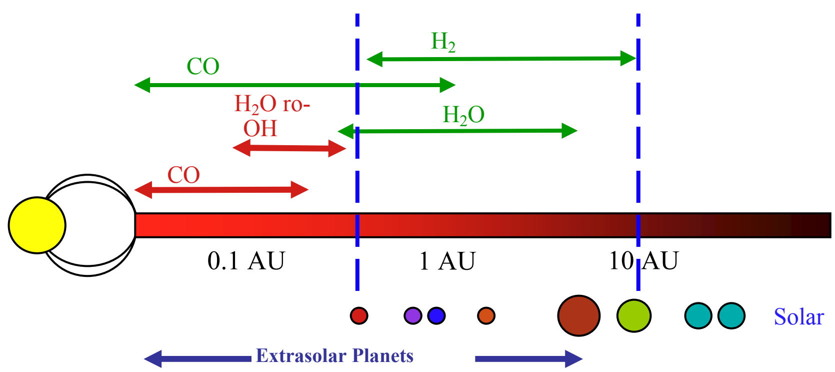

Figure 3. Different molecules and transitions are complementary in the radii they probe. They also complement one another in the related issues of planet formation they can address.

For a disk around a solar mass young star, Figure 3 shows (roughly) our expectations for the most abundant molecules. For example, the CO fundamental will originate inside of 1 AU and therefore probes the conditions relevant to terrestrial planet formation. The H_2 rotational lines, which would detect larger amounts of gas at larger radii, are critical for measuring gas timescales in the giant planet formation region. The 24 μm [Fe I] line straddles these probes in radii. The use of 5 μm CO (emission) is restricted to radii inside of ~ 1 AU, where it is a good probe of thermal, physical, and dynamical structure. The corresponding probe at larger radii will be the mid-IR H_2O lines. Gaseous H_2O is expected to be highly abundant inside of ~ 5 AU, and transitions will be strong enough to measure profiles (if abundances relative to CO are similar to those already measured at small radii). Less abundant species may be too weak to provide good profiles, but their relative chemical abundances will be important for understanding chemical synthesis in disks and the role of turbulent mixing.

2.3.2. From astrochemistry to astrobiology

More than 50 years ago, Stanley Miller demonstrated that amino acids could be synthesized by applying an electrical discharge to a reducing mixture of simple gases, demonstrating how biological compounds can arise abiotically under conditions that were then thought to be similar to those of the early Earth. While the significance of this experiment has diminished over time by the recognition that the atmosphere of the early Earth was probably much less favorable for the origin of biological compounds, more recent developments lead to serious consideration of an extra-terrestrial origin for prebiotic compounds, i.e., the delivery of these to Earth by asteroids, comets, and meteorites. Amino acids, nucleobases, and sugar-related compounds have been identified in some carbonaceous chondrites, a particular class of meteorites. Comets are known to contain molecules of prebiotic interest. Of the approximately two dozen such molecules known, several may react spontaneously in liquid water to produce amino acids or nuclei. Such parent bodies, if they impacted the Earth under the right conditions, may have seeded the Earth with the chemical ingredients necessary for the development of life.

Complex hydrocarbons have also been detected in the interstellar medium, including alcohols, acids, nitriles and aldehydes, such as the simple sugar glycoaldehyde ($CH_2(OH)CHO$). Simple hydrocarbons (e.g., HCN, C_2H_2) can be formed via gas-phase chemistry in cold dense clouds, while simple saturated molecules (H_2O, NH_3, CH_4) are produced by grain surface reactions. Many of the more complex organic molecules (e.g., alcohols, aldehydes) are believed to be the product of grain surface chemistry, but others (e.g., ethers, carboxylic and amino acids) could form through ion-molecule reactions in warm gas after the products of grain surface chemistry have been desorbed.

Hence, a large number of extra-terrestrial organic and prebiotic molecules are known to exist both in the Solar system and the interstellar medium. A better understanding of the inventory, formation and evolution of these molecules in star and planet forming environments is a key goal of astrobiology.

Determining whether prebiotic componds can have an extra-terrestrial origin will require two parallel investigations. One is to measure the presence and quantity of prebiotic material. In the Solar system, this is currently reflected in the inventory of organics found in comets and meteorites. An essential complement to these 'in situ' measurements will be a directed search for prebiotic molecules and their precursors in planet-forming circumstellar disks surrounding young stellar objects. Together, such studies will provide the insight critical to determining whether the ingredients necessary for the origin of life are commonly available within forming planetary systems.

To determine whether such prebiotic molecules can successfully be delivered to Earth via bombardment by minor bodies, and if so, at what rate, represents the next stage in learning whether the ingredients for life on Earth are delivered from external sources. Both Solar system studies and theory provide major clues, but a more general answer to this question depends on deepening our understanding of the range of planetary architectures and the resultant dynamical history of the system. A combined understanding of (1) whether and in what quantity prebiotic molecules are produced in molecular clouds and circumstellar disks, and (2) how and in what quantity such molecules are transported to exo-Earths, would allow one to predict the importance of the delivery of prebiotic compounds on the origin of life.

Mid-infrared spectroscopy with MIRES will be an essential tool for investigating the inventory and content of organic molecules in protoplanetary disks. Most simple and complex hydrocarbon compounds have strong mid-infrared transitions, and a majority of these are accessible to ground-based observations. High-spectral resolution is essential, particularly in searching for rarer molecular species. A given spectral region may be crowded with molecular lines, and lines of more complex molecules will be weak due to lower abundances and the typically larger number of transitions. Thus, very high signal-to-noise observations are required. Broad wavelength coverage, providing access to large numbers of transitions, will also increase the detectability of rare molecules.

2.2.3 Collisional histories of planetary systems

One of the major results from IRAS was the discovery of luminous disks of circumstellar dust surrounding stars that were much beyond the primordial disk phase. These planetesimal belts are the extra-solar analogs of the Kuiper Belt and asteroid belt in our Solar system. Since the processes governing grain removal in these systems can remove the grains on time scales much shorter than the age of the system, the grains are believed to be replenished by recent collisions between planetesimals. Significant collisional debris is likely to be a signpost of an accompanying planetary

system. For one, the colliding bodies, planetesimals, are themselves the building blocks of planets. In addition, the planetesimal belts are thought to be dynamically “stirred” by massive planets, producing the higher eccentricities and inclinations that lead to debris-producing collisions.

Of particular interest in the context of the origin of life on Earth are debris-producing mechanisms that led to the delivery of water and organics to Earth. In the history of our own solar system, the outward migration of Neptune and the accompanying changes in the orbital evolution of Jupiter and Saturn are believed to have triggered a massive destabilization of both the asteroid and Kuiper Belts some 700 Myr after the formation of the solar system. This resulted in the generation of significant collisional debris in both belts and the ejection of planetesimals from the belts into orbits that crossed those of planets in the inner solar system. This view of the dynamical history of the solar system is in good agreement with the cratering record of the inner solar system (on the Moon, Mars, Venus, and Mercury) and may explain the unique period of heavy cratering known as the period of Late Heavy Bombardment (LHB).

A stochastic collisional event such as the LHB may have played a significant role in the delivery of water and organics to Earth. While the delivery of these substances is advantageous to the emergence of life, a more intense bombardment event than the LHB may have instead vaporized the oceans and postponed the emergence of life. In this way, the dynamical evolution of planetesimal belts can have a significant impact on the origin of life, for better or worse. How often and with what intensity do such events occur? While it appears to be impossible to observe directly the dynamical scattering of planetesimals in young planetary systems, detecting the collisional debris produced in LHB-type events provides us with a way to investigate the magnitude and incidence rate of stochastic bombardment events.

The high angular resolution imaging capability of MIRES will be critical to sorting and characterizing statistical samples of debris disks. The study of large samples is needed to establish the frequency of stochastic bombardment events. Thus far, thermal infrared debris disk morphologies are available for only 5 A stars and no later type stars. With its high angular resolution, MIRES will extend these results to more distant objects and larger statistical samples. Detailed morphologies provided by MIRES and measurements of disk surface brightnesses, azimuthal symmetry, and grain sizes will help to determine whether a given system is undergoing a stochastic collisional event or is merely in a state of quiescent grinding of planetesimal belts.

MIRES studies of debris disks will have strong synergy with ALMA. MIRES will be able to characterize the dust morphologies and dust generation rates in asteroidal belts in nearby solar-type stars and at asteroidal to Kuiper Belt distances in disks surrounding earlier type stars. Asteroidal belts will be of particular interest since the LHB event in our own solar system was apparently dominated by projectiles from the asteroidal belt. ALMA will excel at characterizing the spatial morphology of cooler dust at larger distances, in the Kuiper Belt region of disks around solar-type stars and beyond the Kuiper Belt region in disks surrounding earlier type stars.

3. DERIVED REQUIREMENTS

The science case outlined above flows down into several sets of requirements – on the instrument itself, requirements for adaptive optics, and requirements on the telescope site. These are discussed individually below.

An additional requirement is that the resulting instrumental capability be feasible at or close to the time of first light of the TMT facility, given the importance of the scientific questions. For this reason, examination of the requirements includes examination of feasibility.

3.1 Instrument requirements

The basic requirements set by the primary science for the parameters for the spectrograph are summarized below. Discussion of the design implications of these requirements is presented elsewhere[5,6]; the resulting instrument is roughly similar to the high-resolution spectrograph TEXES[1], but with the additional optics and mechanisms required to interface to an adaptive optics system[4].

Table 1. Mid-infrared instrument requirements

Mode	Diffraction-limited (adaptive optics feed)
Wavelength range	4.5-25 μm
Background	Instrument should minimize background increase over natural sky + telescope background
Acquisition camera	Additional near-infrared camera (K band) with field of view at least that of 10-μm imager
Spectroscopy	
Slit length	3"
Slit width	≥ 0.1" (R ≤ 120,000)
Spectral resolving power	60,000-120,000
Spectrograph pixel scale	Approximately diffraction-limited
Spectrograph coverage	>2% contiguous coverage
Imaging	
Slit-viewing camera FOV	15"x15"
Camera pixel scale	Diffraction limited at shortest wavelength (4.5 μm)
Camera focal plane	1k x 1k Si:As array

Additionally, the science cases rely on accumulating moderate-sized statistical samples - from a few dozen up to a few hundred objects. This places a premium on operational efficiency, since time lost to "overhead" can amount to many nights of telescope time when summed over large numbers of objects.

3.2. Adaptive optics requirements

The diffraction limit of a 30-m telescope at mid-infrared wavelengths is significantly better than the image quality produced by natural seeing, even under exceptional conditions. Therefore, an adaptive optics system is required to produce the required image quality. The challenges of such a system are somewhat different from those for an AO system intended for use on an ELT at shorter wavelengths:

The wavefront correction can be relatively modest – good performance is achieved with ~700 nm of residual wavefront error, and excellent performance is achieved with ~300 nm of residual wavefront error. These levels of wavefront error can be produced by much simpler systems than are required for the near-infrared[4,10,11]. A suitable mid-infrared adaptive optics system (MIRAO) is likely to be useful even with somewhat worse than average atmospheric conditions, because well-corrected images should still be possible at the longer wavelengths.

On the other hand, the gains produced by adaptive optics should not be compromised by a large amount of additional thermal background from the AO system. The most transparent regions of the mid-infrared spectrum have very low emissivity, so the primary sources of thermal emission are the telescope, instrument, and adaptive optics system. The combined emissivity of the instrument and telescope should be under 10%; the AO system needs to contribute only a fraction of this amount in additional emissivity to avoid hurting performance. An additional requirement is that this performance should be achieved with realistic technology, ideally avoiding any need for technology development during the AO system design phase.

The baseline MIRAO design[4] has emissivity of roughly 4%, but it could be reduced further if an adaptive secondary is installed on TMT. The effect of this on sensitivity is shown in Figure 4, below.

The targets identified in the key science cases are, in many cases, quite bright in the near-infrared. They can potentially be used for high-order wavefront correction (requires J<12, ideally J<11[4]). This possibility should be taken into account in the design of the AO system and the instrument.

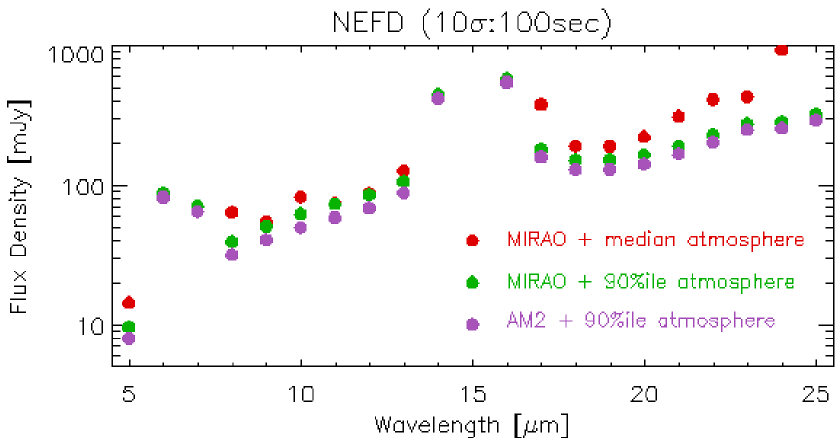

Figure 4. MIRES sensitivity. The top (red) points are for the median atmospheric transmission in 1-μm spectral intervals with the baseline MIRAO system. The middle (green) points are for the 90th percentile atmospheric transmission in the same interval, again with the baseline MIRAO, and the bottom (violet) points are for the 90th percentile transmission where TMT has an adaptive secondary. All the calculations were done for "good" conditions on Mauna Kea, with 1 mm of precipitable water, at 1.4 airmasses: "median" and "90th percentile" refer to transmission within each wavelength interval.

The figure illustrates first of all the difference between median sensitivity and that in the most transmissive spectral regions; this difference is particularly pronounced at the longest wavelengths. The impact of the adaptive secondary is greatest – about 25% - at those wavelengths where atmospheric transmission is best.

A similar plot can be constructed for imaging performance.

3.3. Site and Operational Requirements

Many astrophysically important transitions occur at wavelengths close to those of strong lines in the Earth's atmosphere. For molecules with multiple rotational transitions, it is possible to select a subset at favorable wavelengths, but for some molecules and atoms there are too few transitions to do so. For these, one would like atmospheric absorption to be as low as possible.

This can be achieved by going to higher altitude, by selecting a relatively dry site, and by queue scheduling observations that are sensitive to water vapor or in the wings of strong lines.

The effects of altitude are illustrated in Figure 5. The three panels show atmospheric transmission at three important wavelengths. The upper line is transmission for a typical high altitude site (Mauna Kea), with assumed water vapor columns of 1 and 3 precipitable mm. The bottom line is for a typical low altitude site (La Silla), also with 1 and 3 mm of precipitable water. With the same amount of water vapor, the lower altitude site has worse transmission. In reality, average water vapor column will be significantly higher at the lower site.

While, clearly, the high altitude site provides better performance, conditions at such a site will not be uniformly this dry. In order to make best use of the best conditions, some form of queue scheduling should be implemented. If MIRES is heavily scheduled, it may be possible to get an adequate fraction of "dry" observing time within time scheduled for MIRES. Ideally, though, one would like the ability to use the driest conditions year-round for critical observations.

The potential impact of queue observing is shown in Figure 6, which compares sensitivity for three different levels of water vapor, all for a high-altitude site (Mauna Kea). Over much of the 8-13 μm window the instrument performance is relatively insensitive to water vapor, while for longer wavelengths, and on the edge of the water absorption band at 6 μm, water vapor is critical.

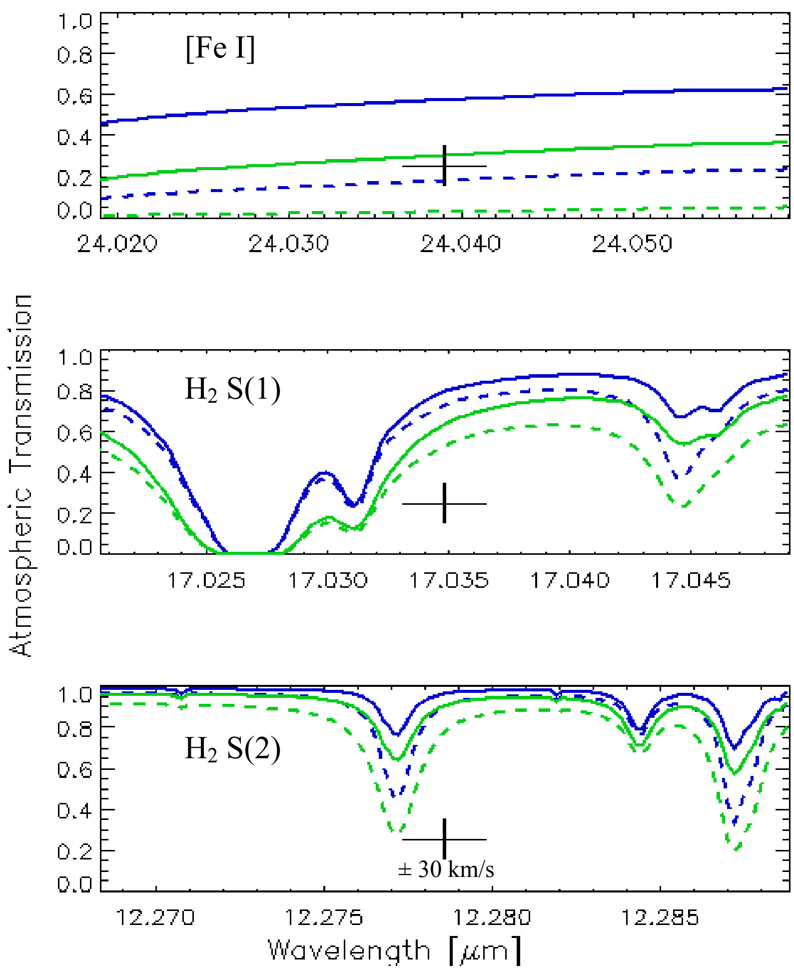

Figure 5. Comparison of low and high altitude sites at selected wavelengths. The three panels show the vicinity of the [Fe I] line, H_2 S(1) and H_2 S(1). The top solid and dashed lines correspond to transmission on Mauna Kea (~4000 m) with 1 and 3 mm of precipitable water; the lower solid and dished lines correspond to transmission at a ~2350 m site, also with 1 and 3 mm of precipitable water.

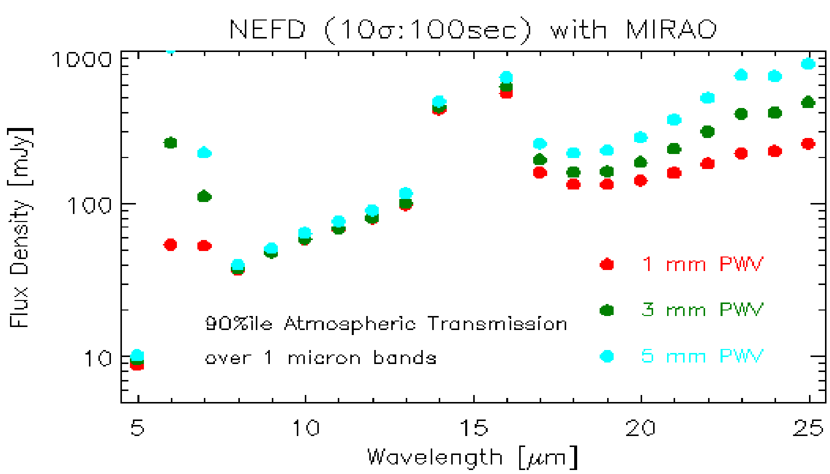

Figure 6. Comparison of sensitivity at three different water vapor levels. Sensitivity shown for 90th percentile transmission within 1-µm spectral intervals, as in Figure 4. The three levels correspond roughly to good, average, and poor conditions for Mauna Kea or similar high-altitude sites.

An additional approach to mitigating the effects of strong atmospheric absorptions is to use the Doppler shift produced by the Earth's orbital motion. In favorable circumstances, this produces velocity shifts of up to 30 km/sec. This is often sufficient to shift the target transition away from the core of a strong absorption line (see Figure 5). In order to take maximum advantage of the Earth's radial velocity, queue scheduling is again advantageous, since different transitions in the same object may be best observed at different times of year. Unlike water vapor, though, the optimum time of year can be predicted in advance.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the Association of Universities for Research in Astronomy (AURA), the California Institute of Technology and the University of California. This work was supported, as well, by the Canada Foundation for Innovation, the Gordon and Betty Moore Foundation, the National Optical Astronomy Observatory, which is operated by AURA under cooperative agreement with the National Science Foundation, the Ontario Ministry of Research and Innovation, and the National Research Council of Canada.

REFERENCES

1. J. H. Lacy, M. J. Richter, T. K. Greathouse, D. T. Jaffe, and Q. Zhu, "TEXES: A Sensitive High-Resolution Grating Spectrograph for the Mid-Infrared," *Pub. Astron. Soc. Pacific* 114, 153-168 (2002).
2. J. E. Nelson and G.H. Sanders, "TMT Status Report," *Proc. SPIE* 6267-60 (2006).
3. A. Glindemann, R. Abuter, F. Carbognani, F. Delplancke, F. Derie, A. Gennai, P. B. Gitton, P. Kervella, B. Koehler, S. A. Leveque, S. Menardi, A. Michel, F. Paresce, T. P. Duc, A. Richichi, M. Schoeller, M. Tarenghi, A. Wallander, and R. Wilhelm, "The VLT Interferometer: a unique instrument for high-resolution astronomy," *Proc SPIE* 4006. 2 (2002).
4. M. R. Chun, J. Elias, B. L. Ellerbroek, M. Liang, T. W. Bond, R. M Clare, A. T Tokunaga, M. Richter, and L. G. Daggert, "Design of the TMT mid-infrared adaptive optics system," *Proc. SPIE* 6272-26 (2006).
5. A. T. Tokunaga, T. W. Bond, J. H. Elias, M. R. Chun, M. J Richter, M. Liang, L. G. Daggert, E. V. Tollestrup, M. E. Ressler, J. S. Carr, and D. Warren, "Design considerations for a high-spectral resolution mid-IR echelle spectrograph on the Thirty-Meter Telescope," *Proc. SPIE* 6269-145 (2006).
6. M. Liang, J. H. Elias, A. T. Tokunaga, M. R. Chun, M. J. Richter, L. Daggert, and T. Bond, "Preliminary optical design for the TMT mid-infrared adaptive optics system and echelle spectrograph," *Proc. SPIE* 6269-150 (2006).
7. D. Silva, ed., "TMT Detailed Science Case", TMT.PSC.TEC.05.067 (2006).
8. J. Najita and J. S. Carr, private communication (2006).
9. C. Knez et al., in preparation (2006).
10. B. L. Ellerbroek et al., "A conceptual design for the Thirty Meter Telescope adaptive optics systems," *Proc. SPIE* 7272-13 (2006).
11. G. Herriot, "NFIRAOS: TMT narrow-field near-infrared facility adaptive optics," *Proc. SPIE* 9272-24.